

# On the distribution function of the information speed in computer network

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## Abstract

We review a study of the Internet traffic properties. We analyze under what conditions the reported results could be reproduced. Relations of results of passive measurements and those of modelling are also discussed. An example of the first-order phase transitions in the Internet traffic is presented.

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## 1. Introduction

For the Internet user the most important parameter of the network is the speed at which one retrieves documents. Anyone browsing the Internet for preprints and articles (xxx.lanl.gov, publish.aps.org, elsevier.nl, iop.org, wpc.com, etc.), or looking for the news and weather, booking tickets, making hotel reservations, etc. asks himself: *why is the Web so slow?* This is precisely the question which motivates our work.

The Internet efficiency depends upon the two main aspects of the network, topology and transport. The topology and connectivity features of the Internet were discussed by Newmann and Barabasi at this Conference [1,2], and our main subject is the review of the Internet transport investigation: its measurements, properties and modelling.

The first set of properties is connected with natural characteristics of human activity. In this con-

nection, the daily working hours lead to a daily periodicity of the web traffic, the work week leads to a weekly periodicity (weekends!), the annual calendar leads to an annual periodicity (winter and summer vacations!), and so on. Holidays and important events (political campaigns, etc.) can also affect the traffic. The latest and most sudden example is the congestion of all news servers on September 11 of 2001 just after the terrorist attack on America.

The second set of the web traffic properties is connected with the fact that the path from one point on the web (e.g., user) and another point (e.g., server) is not stable. The path is often quite complicated and consists of a number of routers, channels, caches, etc., which changes with time because the network constantly develops [3,4]. This reminds us of the ancient philosopher Heraclites, who asserted “You cannot step twice into the same river”. We could say the same about the Internet river. The third set of properties further complicating the measurements is connected with the dynamics of the Internet traffic for many autonomous systems, which leads to the random changes in the

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transport topology and therefore in the timing and loading characteristics.

The knowledge obtained on the Internet traffic properties is reviewed in this article.

## 2. Network traffic: $1/f$ noise and models.

Network traffic has been the subject of intensive investigations especially in the last eight years after WWW technology was invented. Nevertheless, we still do not have a single simple answer to the main question of *why is the Web so slow?*

One of the main difficulties of understanding the Internet nature is that it is neither centrally planned nor configured. It is a good example of the self-organised global structure which is still a self-growing one. People who are running the Internet started in 2000 their annual workshop on the passive and active measurements (PAM) on the Internet. The relation between passive and active measurements is still not understood. Active measurements are easily understood but do not clearly predict actual Internet and Web performance; passive Internet/Web measurements can reflect actual performance but can be hard to interpret. Passive measurement is nothing but data acquisition to log-files of the transactions routinely done by the routers, switches, proxies, caches and workstations. One could find this information in the corresponding log-files. The active measurements could be divided into several groups. The two most extreme are RTT information and modelling of the user activity. RTT (round trip time) between two nodes on the Internet could be obtained, f.e., using the usual Unix command *ping*. The resulting value can be used by many protocols for different reasons like, f.e., for a path optimization or more often just to check whether the given node is accessible or not.

The distribution of RTT times is not trivial and it is the subject of intensive investigation after the pioneering paper of Csabai [5]. Analysing the results of several hundreds of RTTs obtained in two weeks between his workstation in Budapest, Hungary, and an ftp server in Helsinki, Finland Csabai found that the power spectral density could be de-

scribed by power law  $1/f^{1.15}$  in a wide range of frequencies  $f$  from  $10^{-4}$  Hz to 0.5 Hz.

Actually, the self-similarity in computer traffic was found a little bit earlier by Leland et al. [6] for the packet flow density in several local Ethernet networks at the Bellcore Morristown Research and Engineering Center. They found “heavy tails” in the cumulative distribution function of the packet sizes. At that time none of the commonly used traffic models was able to capture this fractal-like behavior.

Takaysu et al. [7] developed a *contact process* (CP) model of jam dynamics on the Internet. They associated a particle with the non-jamming gateway which can reproduce another particle at a neighboring site at a rate  $p$ , and can annihilate (i.e. jammed gateway) spontaneously at a rate  $q$ , and  $p + q \leq 1$ . They found that the survival probability at the critical point ( $\delta = 1 - p/q \rightarrow 0$ ) was proportional to the inverse time  $1/t$ . Moreover, assuming that the RTT times are the two-valued function, taking values  $h$  and 0, they showed that the power spectrum proportional to  $1/f^\alpha$  with value  $\alpha$  bounded,  $0 < \alpha \leq 1$ . This result seems to be supported by the analysis of Ethernet and Internet traffic in a series of papers by Takayusu, et al. [8].

Huisinga et al. [9] introduced a microscopic model for the packet transport on the Internet. Data are divided into small packets of a definite size. These data packets move, for fixed source and destination hosts, due to the structure of TCP/IP, along a temporally fixed route. Therefore, the transport between two specific hosts can be viewed as a one-dimensional process. The cellular automaton model Asymmetric Simple Exclusion Process (ASEP) has an important property - the occurrence of boundary-induced phase transitions [10].

Analysing the power spectrum of the travel times Huisinga et al. [9] identified three phases: free flow characterized by the white noise, congested phase with  $1/f^{1/2}$ -noise at low frequencies and white noise at high frequencies, and critical load phase with  $1/f$ -noise at low frequencies and white noise at high frequencies. They concluded with the important observation that the jamming properties are not related to the structure of the network and rather connected with the paths with critical load.

### 3. Server load and latency times

Although the traffic models discussed in the previous section seem to explain some peculiarities of the Internet traffic at the critical path load, some recently observed phenomena connected with the server critical load (news servers!) are still not understood.

Barford and Crovella [12,11] find surprising effect of server load. When the network is heavily loaded (i.e., packet loss rates are high), it is not uncommon for a heavily loaded server to show a *better* mean response time than a lightly loaded server. Their measurements suggest that this may be because heavily loaded servers often show lower packet loss rates, and since packet losses have dramatic effects on transfer latency, this can reduce the mean response time.

In the rest of this section I will analyse the probability distribution function of the latency times and arrive at the simplest experimental setup having the property observed by Barford and Crovella [12,11].

It is a commonly accepted picture (see, f.e., Figure 1 in the paper by Helbing, et al. [13]) that the distribution of download times (i.e., latency times) is log-normal and that this property leads to the  $1/f$  property of the Internet traffic.

In fact, the distribution function of latency times is multi peaked [3]. The peaks could be associated with two sets of factors. The first ones are connected with the different throughput of the particular paths between user workstation and destination servers. This fact is clearly visible for some preprint and reprint library servers placed in the Far East. The next set of factors is connected with the traffic content. The speed of document retrieval depends on the type of document: text, image, binary file, audio, video, etc. Indeed, it is practically possible to decompose the distribution function into the more elementary ones analysing the content of the proxy server log files and using the above-mentioned two sets of factors. Nevertheless, even in this case, the distribution function of elementary processes like taking files from a particular archive (say, Los Alamos Archive) to a given workstation, the distribution more often demon-

strates two peaks [14].

The same effect of multi peaked distributions could also be obtained analysing RTT times on a short path between workstation and border router. Figure 1 shows a histogram of RTT times between workstation (connected to 100 Mbps/s Ethernet fiber-optic campus network of Chernogolovka Science Park (AS 9113)) and border Cisco router BNS045 (147.45.20.221) of FREENet. AS 9113 and BNS045 connected by a 2 Mbps ATM channel. Workstation and border router are separated by only one LAN router. The large and narrow peak at about 7 ms is associated with the round trip time of a 64 bit ping packet in the path connecting three devices with an empty 2 Mbps ATM channel. The next and wide peak at about 750 ms could be associated with the router congestions. The fact that these peaks are well separated is due to some particular features of the TCP protocol. This picture is a clear demonstration of the nonlinear response of the router.

Moreover, we found [14] that RTT times inside a single workstation exhibit usually two peaks in the probability distribution function of RTT times. We performed an analysis of the RTT times of the Unix ping command on the internal network interface

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ping -i S -s 56 127.0.0.1
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where  $S$  is the interval in seconds between two consecutive ping packets of the size of 56 bytes (the ping packet contains also 8 additional bytes, i.e. the total packet size is 64 bytes). We vary interval  $S$  and accumulate data for  $S = 1, 10, 20$  and 50 seconds. Figure 2 shows histograms  $P(t_R)$  of RTT times calculated in intervals of 0.004 ms. This histograms were obtained from the results of 50000 pings grouped in 5 groups and then averaged. Fluctuations from one group to another are small enough.

All histograms have two peaks, placed at about  $t_R^{(1)} = 1.28 - 1.29$  ms and  $t_R^{(2)} = 1.35 - 1.36$  ms. For the pings with interval  $S = 1$  s there are higher probabilities that measured RTT time will be about  $t_R^{(1)}$ . For the pings with interval  $S = 50$  s this probability is higher at the value of about  $t_R^{(2)}$ . For the intermediate interval between pings

$S = 20$  s both peaks have approximately the same height, and the result of the measurement of  $t_R^{(1)}$  or  $t_R^{(2)}$  will be equally probable.

It is better to plot RTT times ranked ascendingly as shown on Figure 3. Changing the axes and their directions one could find that this curve after normalization is nothing but a cumulative distribution function of RTT times. In fact, the curves in Figure 2 could be obtained from Figure 3 with proper differentiation. Figures 2-3 clearly demonstrate that by varying the interval between pings we have some kind of “first-order phase transition” between states characterised by RTT time values  $t_R^{(1)}$  and  $t_R^{(2)}$ . It is not a true phase transition because we could not associate any order parameter with the process.

The effect we found is stable and reproducible. We obtain the same behaviour for the number of Unix workstations of different types disconnected from the network and not running any processes except minimal configurations. The only difference is the values of  $t_R^{(1)}$  and  $t_R^{(2)}$  RTT times and the interval  $S$  times. So, this effect could be considered as the universal one.

We associate this effect with the cache memory organization. It seems that the difference between the values of  $t_R^{(2)}$  and  $t_R^{(1)}$  is the time necessary to upload the ping process to the cache memory. Unix systems were running some processes which could oust ping procedure from the cache and thus increase the RTT time. A detailed analysis will be published elsewhere [14] as well the the model of the process.

We analysed the power spectrum of the RTT signals [5] and found that in all cases it could be approximated with the  $1/f^\alpha$  law with  $\alpha = 2$  for the low frequencies and demonstrated white noise at the high frequencies. Nevertheless, this analysis has to be considered with more caution; we found in one measurement that just one fluctuation in RTT time which gives  $t_R = 106$  ms obtained in any experiment with  $S = 50$  s has changed our power spectrum drastically. Excluding this enormous fluctuation all results are very stable and reproducible.

## 4. Discussion

We have to note that the effect of first-order phase transition which we found to be the influence of the cache memory, could be even more universal. In fact, all servers usually use cache memory, and the effect of the higher productivity of the servers [12,11] under the heavy load could be explained as an effect of the heavy cache memory usage as well.

Most of the models of Internet traffic are based on the assumption that the routers are nothing but queues. It seems that this is not always the case and more sophisticated nonlinear models of the elements of the network should be considered. Most of the nodes which are just single routers nowadays consist of several devices which separately work as switches, or routers, or name servers, or proxy-cache servers with rather complicated intercommunications and interactions.

## Acknowledgements

Thanks are due to Serge Krashakov and Timofey Rostunov for help and discussions. This work is supported by the twin research program of the Landau Institute and the Ecole Normale Supérieure de Paris and by RFBR under projects 99-07-18412, 99-07-90084, and 01-07-90119.

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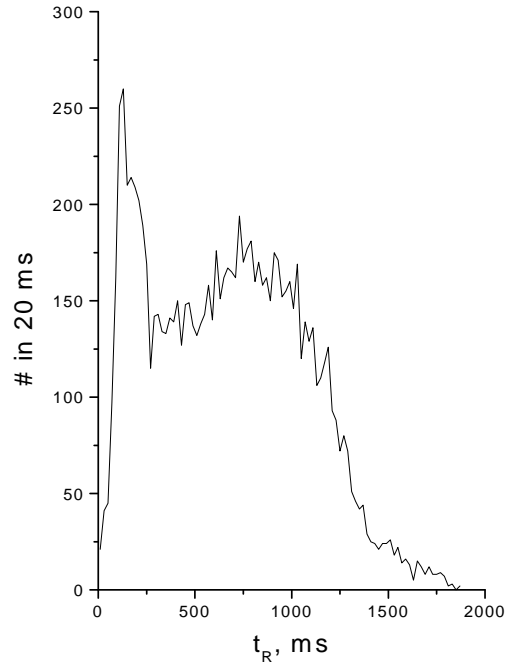


Fig. 1. Typical histogram of RTT times (in *ms*) between workstation and router BNS045 calculated as number of RTT time values within an interval of 20 *ms*.

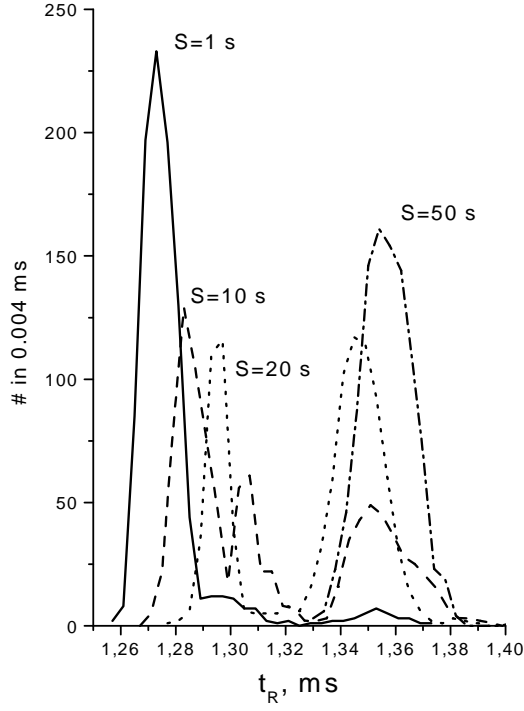


Fig. 2. Histograms of internal ping RTT times calculated in intervals of  $0.004\text{ ms}$  for the interval times between two ping packets  $S = 1\text{ s}$  (solid line),  $S = 10\text{ s}$  (dashed line),  $S = 20\text{ s}$  (dotted line), and  $S = 50\text{ s}$  (dash-dotted line).

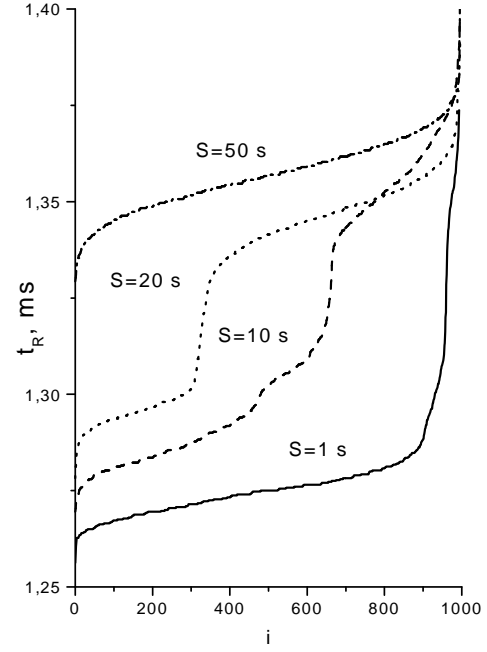


Fig. 3. Internal ping RTT times ranked ascendingly for the interval times between two ping packets  $S = 1\text{ s}$  (solid line),  $S = 10\text{ s}$  (dashed line),  $S = 20\text{ s}$  (dotted line), and  $S = 50\text{ s}$  (dash-dotted line).